PB82-241902

Rotating Biological Contactors
Second Order Kinetics

(U.S.) Municipal Environmental Research Lab.
Cincinnati, OH

Apr 82

U.S. Department of Commerce
National Technical Information Service
NTIS

EPA 600/D-82-319

PB82-241902

ROTATING BIOLOGICAL CONTACTORS - SECOND ORDER KINETICS

by

Edward J. Opatken
U.S. Environmental Protection Agency
Wastewater Research Division
Municipal Environmental Research Laboratory
Cincinnati, Ohio 45268

Presented at

First International Conference on
Fixed Film Biological Processes

Kings Island, Ohio
April 20-23, 1982

REPRODUCED BY
NATIONAL TECHNICAL
INFORMATION SERVICE
U.S. DEPARTMENT OF COMMERCE

TECHNICAL REPORT DATA
(Please read Instructions on the reverse before completing)

1. REPORT NO.	2.	3. RECIPIENT'S ACCESSION NO.
EPA 600/D-82-319		PB82 241902

4. TITLE AND SUBTITLE	5. REPORT DATE
ROTATING BIOLOGICAL CONTACTORS - SECOND ORDER KINETICS	April 1982
	6. PERFORMING ORGANIZATION CODE

7. AUTHOR(S)	8. PERFORMING ORGANIZATION REPORT NO.
Edward J. Opatken	

9. PERFORMING ORGANIZATION NAME AND ADDRESS	10. PROGRAM ELEMENT NO.
Wastewater Research Division Municipal Environmental Research Laboratory Cincinnati, Ohio 45268	AZB1B, B-113, D 2/23
	11. CONTRACT/GRANT NO. Inhouse

12. SPONSORING AGENCY NAME AND ADDRESS	13. TYPE OF REPORT AND PERIOD COVERED
Municipal Environmental Research Laboratory-Cinti,OH Office of Research and Development U. S. Environmental Protection Agency Cincinnati, Ohio 45268	Interim, August 1980-April 1982
	14. SPONSORING AGENCY CODE EPA/600/14

15. SUPPLEMENTARY NOTES

16. ABSTRACT

Rotating biological contactors (RBC) have been employed for treating municipal wastewaters within the United States since 1970. The RBC process lends itself to kinetic interpretation because of the sequential stages employed in the operation. This mode of operation enables the substrate concentration to be determined after various time intervals to obtain kinetic data for interpretation.

An analysis was conducted on previously published data, which contained the concentration of soluble chemical oxygen demand (COD) at various stages in the treatment train. The time intervals were calculated based on the hydraulic loading rate and the liquid volume in each stage. The data was incorporated into a number of rate equations and a second order reaction rate equation gave a good correlation for the published data. This technique was repeated with other published data on the disappearance of sCOD at different stages in the treatment train and again the data obeyed a second order rate equation.

A project was initiated to obtain interstage data on soluble COD at three RBC facilities within a 100-mile radius of Cincinnati. The results again gave a strong correlation that RBC obey a second order reaction rate equation.

The analytical results from nine RBC plants were compared with the predicted interstage data determined by using a second order rate equation. The results showed that second order kinetics was able to predict interstage soluble organic data at eight of the nine plants.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
Waste Treatment Biochemical Oxygen Demand Oxygen transport mechanisms Mathematical models Wastewater	Rotating Biological Contactors Hydraulic Loading Mass Loading	13B

18. DISTRIBUTION STATEMENT	19. SECURITY CLASS *(This Report)*	21. NO. OF PAGES
Release to public	Unclassified	
	20. SECURITY CLASS *(This page)*	22. PRICE
	Unclassified	

EPA Form 2220-1 (9-73)

Rotating Biological Contactors - Second Order Kinetics

The RBC process is uniquely adaptable for kinetic studies on secondary treatment of wastewater. Secondary treatment, for this specific kinetic study, is defined as the removal or reduction of soluble substrate with time. The substrate is identified in the reaction phase as soluble chemical oxygen demand (sCOD) and/or soluble biochemical oxygen demand (sBOD). The reduction of insoluble oxygen demanding material is not applicable since:

1. It is the function of the reactor (RBC) to convert soluble organic matter into carbon dioxide and insoluble matter for later removal by the secondary clarifier.
2. The use of unfiltered oxygen demand would require the kinetic study to treat the RBC process as a heterogeneous reaction instead of a homogeneous reaction.

The applicability of the RBC process to study reaction kinetics is attributed to its process configuration, and operation mechanism. The RBC process usually consists of modular units (shafts) that are normally installed in series. Each RBC shaft contains either 100,000 sq ft (9,300 m^2) or 150,000 sq ft (14,000 m^2) of surface area. The volume of the trough to surface area of the discs (V/SA) ratio is fixed by the manufacturer at 0.12 gal/sq ft (4.9 L/m^2). These basic geometric standards enable the reaction time to be determined at each stage. Each RBC shaft rotates at approximately 1.6 rev/min or at a peripheral speed of 60 ft/min (18.3 m/min). The rotation of the RBC mixes the wastewater, and thus simulates a stirred tank reactor. The RBC is divided into independent stages by a baffle which enables the disappearance of soluble oxygen demand to be quantified at each stage for specific time intervals.

Data for the first five runs on both air and mechanical drive systems were plotted showing the concentration of sCOD at specific time intervals based on the retention time within a stage. The curves for only three of these runs are shown in Figures 2 and 3 to improve the clarity of the plot. The plot indicated that the removal rate of sCOD decreased as the reaction time increased, which indicated second order rates of reaction. The data were then used to plot $\Delta C/\Delta t$ vs C^2 to obtain the reaction rate constant from the slope of the plot. For the five runs the mean reaction rate constant was 0.015 L/mg·h for the mechanical drive system and the mean refractory concentration for these five runs was 25 mg sCOD/L. The air drive system had a mean reaction rate constant of 0.025 L/mg·h and the mean refractory concentration was 21 mg sCOD/L. These data are shown in Table 1.

Table 1. Reaction Rate Constants Derived from R. J. Hynek Data

Run Number	k (L/mg·h)	Correlation Coefficient	Refractory sCOD (mg/L)
VA-M	0.013	0.999	32
VA-A	0.015	0.999	30
VB-M	0.018	0.997	27
VB-A	0.024	0.995	26
V1A-M	0.019	0.998	27
V1A-A	0.022	0.996	24
V1B-M	0.013	0.999	14
V1B-A	0.056	0.987	0
V1C-M	0.014	0.997	26
V1C-A	0.010	0.999	25
mean value (M):	0.015	0.998	25
mean value (A):	0.025	0.995	21

M = Mechanical drive
A = Air drive

Second order kinetics.

The published data by A. A. Friedman[1] on the disappearance of sCOD was incorporated into the rate expression for a second order equation.

where $r = \frac{\Delta C}{\Delta t} = kC_n^2$

$r = \frac{\Delta C}{\Delta t}$ = rate of disappearance of sCOD, mg sCOD/L

k = reaction rate constant, L/mg·h

C_n^2 = the square of the concentration of sCOD in the nth stage, $(mg/L)^2$

$\Delta C = (C_{n-1}-C_n)$ = the difference in concentration of the influent into a stage from the concentration within that stage in mg sCOD/L

Δt = reaction time in h

A plot of $\Delta C/\Delta t$ vs C^2 is shown in Figure 1. The slope of the line is the reaction rate constant, k, which has a value of 0.0062 L/mg·h. The intercept on this curve should theoretically go through zero; however, there is a fraction of sCOD that can be assumed as refractory. This fraction will not undergo biochemical conversion and is represented by the "x" intercept. This fraction is 33 mg sCOD/L for the synthetic influent used by A. A. Friedman in his RBC pilot plant study.

Another published paper by R. J. Hynek[2] was used to obtain interstage data on the disappearance of sCOD. The hydraulic loading rate was used to calculate the residence time in each stage and again the data was incorporated into a second order rate expression. The data consisted of results from both a mechanical drive and an air drive RBC shaft.

Field verification of second order reaction.

Three RBC facilities within a 80 km radius of the Andrew W. Breidenbach Environmental Research Center were sampled to obtain interstage data on the disappearance of sCOD. The three facilities were LeSourdsville, Ohio; Indian Creek (Cleves, Ohio); and Brookville, Indiana. Table 2 summarizes the characteristics of these facilities.

Table 2. Characteristics of RBC Facilities

	LeSourdsville	Indian Creek	Brookville
No. of trains	4	2	3
No. of shafts	20	6	3
No. of stages per train	5	3	4
Diameter of disc, ft (m)	12(3.7)	12(3.7)	12(3.7)
Stages per shaft	1	1	4
Total surface area, ft^2	2.6×10^6	4.8×10^5	3.0×10^5
(m^2)	(2.4×10^5)	(4.5×10^4)	(2.8×10^4)
Surface area, per stage ft^2	1×10^5* 1.5×10^5**	8×10^4	2.5×10^4
(m^2)	(9,300)* (14,000)**	(7,500)	(2,300)
Design flow, mgd	4.0	0.5	0.6
(m^3/d)	(15×10^3)	(1.9×10^3)	(2.3×10^3)
Design hydraulic load, gpd/sq ft	1.5	1.0	2.0
($m^3/m^2 \cdot d$)	(0.062)	(.042)	(0.081)

*Stages 1&2
**Stages 3,4,5

On each sampling date, the following were obtained:

1. Influent, effluent, and stage samples
2. Influent and effluent temperature
3. Plant flow rate during the sampling period

The samples were filtered and stabilized with acid before submittal to the MERL Waste Identification and Analysis Section for sCOD analysis.

The data were then incorporated into a second order reaction rate equation to determine the rate constant for these systems.

The interstage data on sCOD obtained for LeSourdsville were treated in the following two modes. The first mode consisted of plotting sCOD against time and a curve was drawn to represent an approximate fit.

The data from this curve were used to determine the reaction rate constant by determining the slope when $\Delta C/\Delta t$ was plotted against C^2. The C^2 intercept was used to predict the refractory portion of the sCOD. The results are shown in Table 3.

Table 3. Reaction Rate Constants for LeSourdsville

Run Number	k (L/mg·h)	Refractory sCOD, (mg/L)
L0815	0.016	37
L0825	0.028	41
L0903	0.032	6
L0909	0.018	21
L0925	0.023	36
L1002	0.015	28
L1008	0.022	43
LI1017	0.015	47
LII1017	0.026	26
LI1024	0.019	30
LII1024	0.026	36
LI1031	0.026	27
LII1031	0.021	16
LI1105	0.009	49
mean value:	0.021	32
σ:	0.0062	12

A second approach was to combine the data from all the runs to obtain a mean value for the influent, the four intermediate stages, and the effluent. A plot of the disappearance of sCOD with time is shown in Figure 4. The reaction rate constant, k, was determined from the slope of the line shown in Figure 5, where $\Delta C/\Delta t$ was plotted against C^2. The reaction rate is 0.024 L/mg·h and the refractory portion is 40 mg/L sCOD. The k value of 0.024 L/mg·h is similar to the k value of 0.021 L/mg·h obtained by determining the mean of the 14 individual runs at LeSourdsville.

The k value at LeSourdsville also is similar to the k value obtained from the Hynek data at the South Shore plant, which is 0.015 for mechanical drive and 0.025 L/mg·h for air drive RBC.

There are wide variations in the analytical data from Indian Creek and these may be attributed to the low level of sCOD in the influent and the long residence time, which at times were over 6 hours. The maximum sCOD obtained at Indian Creek was 105 mg/L and only one sample out of 36 was above 100 mg/L. Another factor that impaired the analyses at Indian Creek was the physical layout which consisted of only three stages. This limited the number of sample points and reduced the probability of determining a curve for representing the disappearance of sCOD.

There were nine sampling dates at Indian Creek. Of the nine dates, four were discarded because a curve could not be drawn that would adequately represent the data to describe the disappearance of sCOD. Figure 6 is an example of a wide scatter analytical result that could not be used in the data reduction. Figure 7 is an example of the disappearance of sCOD with time that could be represented by drawing a curve to represent the selected data. For the five dates that could be described by drawing the best curve for the disappearance

of sCOD with time, the reaction rate constant was 0.018 L/mg·h and the mean sCOD refractory was 27 mg/L. Again, the data from these five runs showed a k value similar to the value at LeSourdsville and by Hynek, even though the level of influent sCOD was significantly below the sCOD levels at the other locations.

The result at Indian Creek behaves as though it were biochemical reaction rate limited and the kinetics obey a second order rate expression. The Indian Creek results show that the low level of sCOD in the influent does not alter its kinetic behavior, and obeys a second order rate expression, whose reaction rate constant is similar to the values obtained at LeSourdsville and with Hynek data.

Oxygen transfer limitation.

During Hynek's test, four runs were operated at a significantly higher hydraulic loading rate, ranging between 2.1 and 2.9 gpd/sq ft (86 to 120 $L/d \cdot m^2$). This, in effect, reduced the reaction time by approximately 50%. To accomplish the same sCOD reduction at the high hydraulic loading, as was obtained at the low hydraulic loading, would require doubling the oxygen transfer rate and an adequate level of biomass to handle the additional sCOD removal requirements resulting from the increase in the hydraulic loading rate.

The plot of sCOD with time is represented by Run VIII for the air drive system and is shown in Figure 8. The data show a linear relationship for the disappearance of sCOD with time. This relationship indicates zero order kinetics. A possible explanation is; as the hydraulic loading increased there was insufficient time to transfer the oxygen required for converting the sCOD; thus changing the system from a biochemical reaction limiting process into an oxygen transfer limiting process; and the kinetic rate changed from a second order expression into a zero order expression.

The Brookville, Indiana facility was sampled on 10 dates. The data reduction for the ten sampling dates resulted in an apparent oxygen limiting operation.

A plot of sCOD against time for the Brookville data showed that seven of the ten dates could best be represented by a zero order rate equation. The data were combined to obtain a mean value of sCOD at each of the four stages and the average retention time at each stage. These values are plotted in Figure 9 and show an excellent correlation for a zero order rate equation.

A comparison was made of the loading levels at LeSourdsville, Indian Creek, and Brookville. A significantly higher loading is evident at Brookville when compared with LeSourdsville or Indian Creek.

The pseudo oxygen mass transfers were calculated for the first stage of the RBC at LeSourdsville, Brookville, and Indian Creek. A sample calculation for the pseudo oxygen transfer at LeSourdsville follows.

The hydraulic loading at LeSourdsville averaged 0.82 gal/d·sq ft

$$0.82 \frac{\text{gal}}{\text{d·sq ft}} \times \frac{\text{d}}{24\text{h}} \times [2 \times 100{,}000 + 3 \times 150{,}000]\ \text{sq ft} \times \frac{3.8\ \text{L}}{\text{gal}} =$$

$$0.82 \frac{\text{gal}}{\text{d·sq ft}} \times \frac{\text{d}}{24\text{h}} \times 650{,}000\ \text{sq ft} \times 3.8 \frac{\text{L}}{\text{gal}} = 85{,}000\ \text{L/h}$$

The oxygen required to satisfy the disappearance of 54 mg/L of sCOD in the first stage is determined by:

$$85{,}000 \frac{\text{L}}{\text{h}} \times 54 \frac{\text{mg}}{\text{L}} \times \frac{1}{100{,}000\ \text{sq ft}} = \frac{37\ \text{mg}\ O_2}{\text{h·sq ft}} \quad \left(400\ \text{mg}\ O_2\right)_{\text{h·m}^2}$$

Table 4. Loading Levels at the RBC Facilities

	LeSourdsville	Brookville	Indian Creek
Hydraulic loading, gpd/sq ft ($L/d \cdot m^2$)	0.88 (36)	1.5 (62)	.5 (20)
Influent, mg sCOD/L	118	288	65
Retention time, h	3.5	2.0	6.0
Pseudo oxygen transfer, $mgO_2/h \cdot sq$ ft, (first stage) ($mgO_2/h \cdot m^2$)	37 (400)	48 (520)	9 (100)

It is evident from this comparison that Brookville has 170% greater hydraulic loading than LeSourdsville and the influent concentration in sCOD is 240% greater at Brookville resulting in an exceptionally high organic loading. The oxygen mass transfer is assumed to be at a maximum, and the limiting factor at Brookville appears to be oxygen transfer rate limited.

If it is assumed that Brookville were limited by a second order rate equation with a rate constant equal to the rate constant obtained at LeSourdsville, 0.021 L/mg/·h, then the disappearance of sCOD would follow the curve as shown in Figure 10. The concentration leaving the first stage, 0.5h reaction time, is 123 mg/L. The pseudo oxygen transfer rate to achieve this level of reduction is 158 mg/h·sq ft (1700 $mg/h \cdot m^2$). This is more than 4 times the pseudo oxygen transfer rate calculated for LeSourdsville and 3 times the actual rate calculated for Brookville. It is for these reasons that the oxygen transfer rate is believed controlling the reaction mechanism at Brookville.

The selection of the three facilities, LeSourdsville, Brookville and Indian Creek, was based on the proximity of these sites to MERL. Yet these three facilities provide a good mix for this evaluation because of the wide

variation in their loadings.

1. LeSourdsville operates at an organic loading that appears to be within 20% of the upper limit for oxygen mass transfer rates and behaves as though it were biochemical reaction rate limited.
2. Brookville operates at an organic loading that appears to be limited by the oxygen mass transfer rate.
3. Indian Creek operates at an organic loading considerably below LeSourdsville and appears to follow a biochemical reaction rate limting process, whose rate constant is similar in value to the rate constant obtained at LeSourdsville and from Hynek.

When the hydraulic load increased, as Hynek did in his evaluation, then the process appears to change from a kinetically limited system to an oxygen limited process.

These results present a new approach in the analyses of RBC performance. The applicability of a second order reaction rate expression to follow the disappearance of the soluble organic fraction was demonstrated with Friedman's pilot plant data, Hynek data, LeSourdsville, and Indian Creek.

The second order expression failed to follow the disappearance of sCOD with time at Brookville, and with Hynek results when the hydraulic loading was doubled. These two operations obeyed zero order kinetics and were assumed to be oxygen mass transfer limited.

The similar k values obtained from RBC's at different field sites treating municipal wastewaters indicates that the reaction rate constant, k, can be used to predict the performance for RBC's when they are employed for secondary treatment. For a series of stirred tank reactors or RBC stages, the concentration of soluble organics can be determined at any stage in the process by use of Levenspiel's equation(3) if the following parameters are known:

1. Reaction rate constant based on sCOD or sBOD, L/mg·h
2. Residence time, h
3. Influent organic concentration, mg/L

Levenspiel's equation for staged reactors that follow second order kinetics is mathematically derived from a mass balance, and is applicable for calculating the soluble organic concentration at any stage. The equation is:

$$C_n = \frac{-1 + \sqrt{1 + 4\,(kt)(C_{n-1})}}{2(kt)}$$

where C_n = concentration of soluble organics in n-stage, mg/L

k = second order reaction rate constant, L/mg·h

t = residence time, h

C_{n-1} = influent soluble organic concentration to stage n, mg/L

This equation can then be programmed into a computer and by inserting the number of stages, n, the initial concentration, C_{n-1}, the residence time within each stage, t, and the reaction rate constant, k; the concentration, C_n, in terms of soluble organics can be readily obtained at any stage in the process train.

To test the applicability of second order kinetics to predict the concentration of soluble organics in any stage of a RBC train, interstage data was obtained from Ianone[4] on the disappearance of sBOD at 9 plants using air drive RBC. The results obtained by Hynek[2] and analyzed earlier in this paper to obtain k values based on sCOD for both air and mechanical drive RBC also included interstage data on the disappearance of sBOD. Hynek's data with sBOD using air drive shafts were incorporated into the second order rate expression to obtain a reaction rate constant for sBOD of 0.083 L/mg·h. The k value was incorporated into Levenspiel's equation to predict the sBOD concentration at any stage for each of the 9 air drive RBC plants. These results are shown in Table 5, and are displayed with the actual results for comparative purposes.

Table 5. Comparison of the Predicted and Actual Disappearance of sBOD

Cleves

Shafts/Stage = 1-1-1

t(h) = 2.5, 2.5, 2.5

	Predicted	Actual
C_{in} =		40
C_i =	12	8
C_2 =	5	5
C_3 =	3	3

Enumclaw

Shafts/Stage = 3-1-1-1

t(h) = 1.4, .46, .46, .46

	Predicted	Actual
C_{in} =		168
C_1 =	34	14
C_2 =	20	9
C_3 =	13	7
C_4 =	10	6

Lancaster

Shafts/Stage = 1-1-1-1.5**

t(h) = 1.4, 1.4, 1.4, 2.2

	Predicted		Actual
C_{in} =			218
C_1 =	39	78*	78
C_2 =	15	22	22
C_3 =	8	10	14
C_4 =	4	5	8

Lower East Fork

Shafts/Stage = 1.5-1-1-1

t(h) = .97, .64, .64, .64

	Predicted	Actual
C_{in} =		20
C_1 =	11	11
C_2 =	8	6
C_3 =	6	5
C_4 =	5	5

*Assume overloaded first stage and determine concentrations of sBOD in succeeding stages.

**High density media

C_{in} = influent

Table 5. Comparison of the Predicted and Actual Disappearance of sBOD (cont'd)

Woodburn

Shafts/Stage = 4-2-1.5-1.5

t(h) = 1.69, .84, .63, .63

	Predicted	Actual
C_{in} =		226
C_1 =	37	28
C_2 =	17	12
C_3 =	11	7
C_4 =	8	7

Greenwood Springs

Shafts/Stage = 1-1-1-1.5

t(h) = .56, .56, .56, .84

	Predicted	Actual
C_{in} =		43
C_1 =	22	20
C_2 =	13	14
C_3 =	9	4
C_4 =	6	5

Dodgeville

Shafts/Stage = 2-1-1

t(h) = 2.6, 1.3, 1.3

	Predicted	Actual
C_{in} =		37
C_1 =	11	9
C_2 =	7	7
C_3 =	4	4

West Dundee

Shafts/Stage = 1-1-1.5

t(h) = .76, .76, 1.2

	Predicted	Actual
C_{in} =		101
C_1 =	33	33
C_2 =	16	15
C_3 =	9	8

Hartford

Shafts/Stage = 1-1-1-1

t(h) = .25, .25, .25

	Predicted	Actual
C_{in} =		17
C_1 =	13	13
C_2 =	11	12
C_3 =	9	9
C_4 =	8	8

There is good agreement between the predicted and actual sBOD at seven of the nine plants. There was a difference at Enumclaw and Lancaster. The calculation for Lancaster was modified by assuming an inadequate oxygen transfer rate in the first stage, due to the high organic loading, and then applying second order kinetics to the following stages. By using the actual value of 78 mg/L sBOD, that was obtained in the second stage, as the initial concentration, and then calculating the sBOD in the ensuing stages, good agreement was then obtained for Lancaster between the predicted and actual sBOD concentrations. There is no explanation that can be theorized at this time for the discrepancy at Enumclaw. An analysis similar to Lancaster is not valid because the actual concentration of sBOD in the first stage was considerably below the predicted value, and therefore oxygen transfer requirements were satisfied at Enumclaw.

These results provide added evidence that RBC obey second order kinetics and when the reaction rate constant is known, can be used to predict performance and design optimum train configurations.

References

1. Friedman, A. A. "Kinetic Response of Rotating Biological Contactors," 31st Annual Purdue Industrial Waste Conference, 1976.

2. Hynek, R. J., and Chou, C.S. "Development and Performance of Air Driven Rotating Biological Contactors," 31st Annual Purdue Industrial Waste Conference, 1976.

3. Levenspiel, O. Chemical Reaction Engineering, John Wiley & Sons, 124-149, 1972.

4. Iannone, J., Personal communication (Roy F. Weston), December 7, 1981.

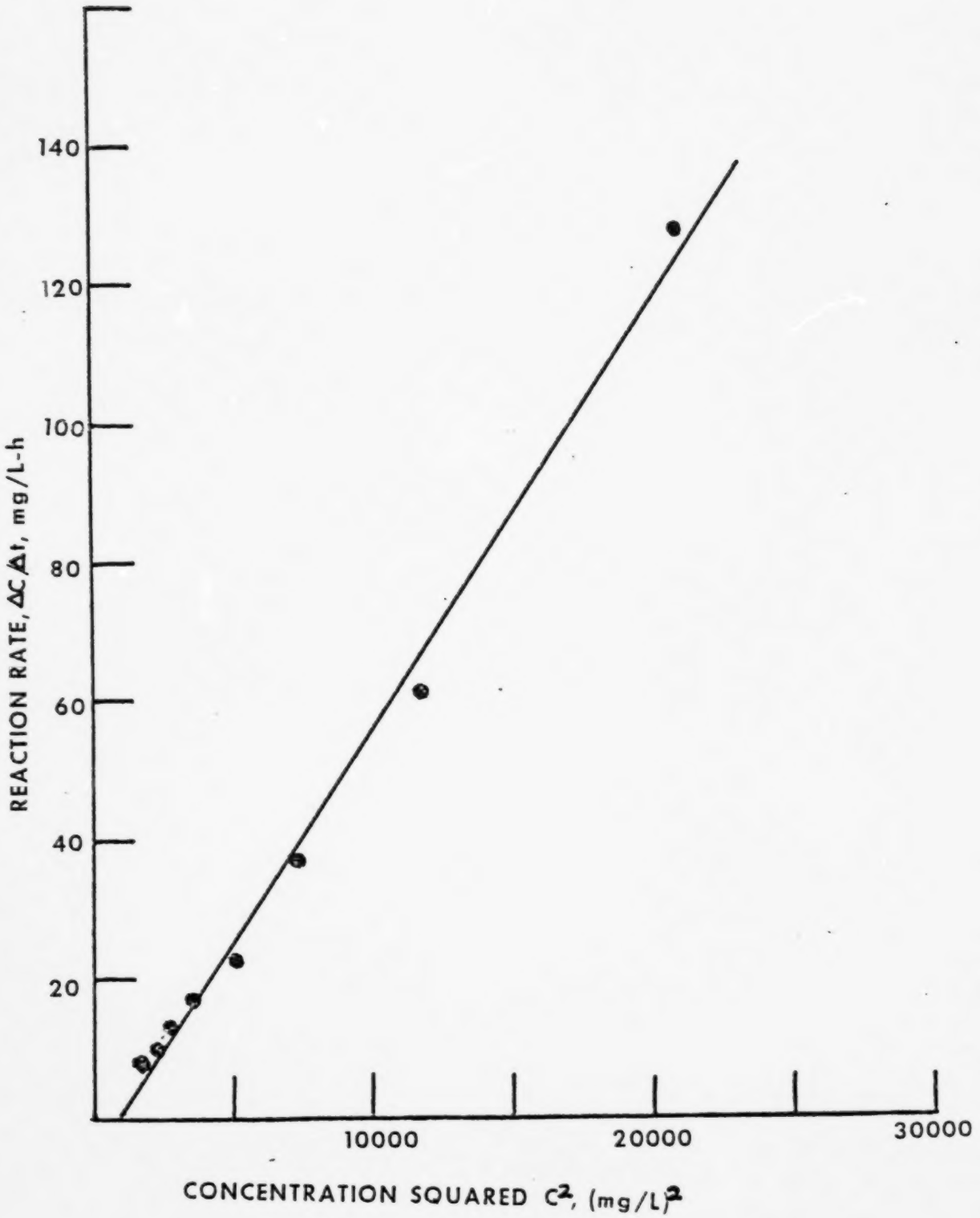

Figure 1. Reaction rate at various concentrations squared.

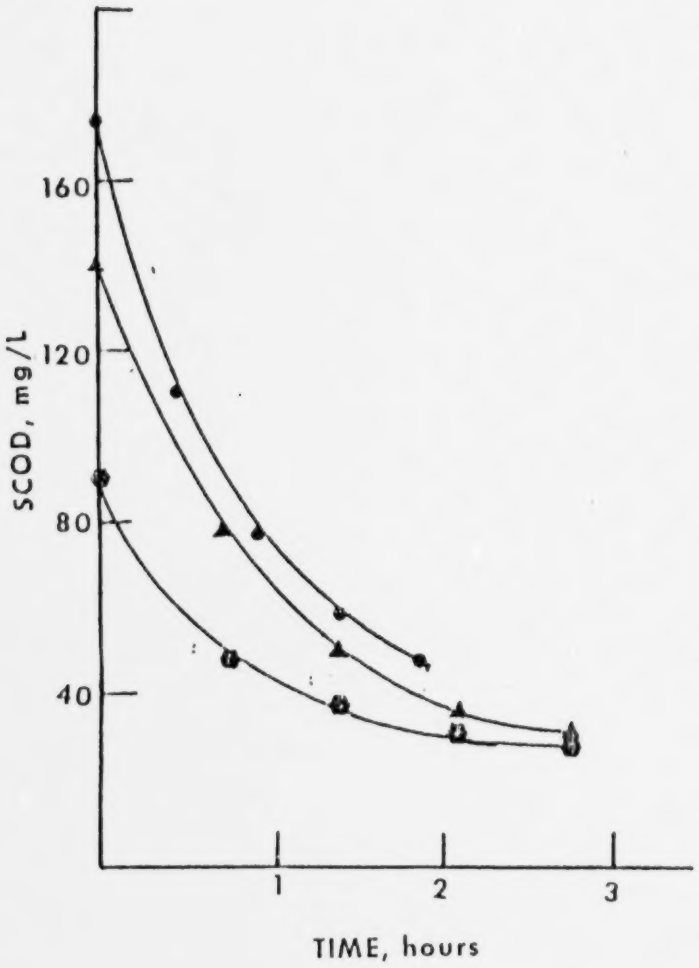

Figure 2. Air drive — Disappearance of sCOD with time.

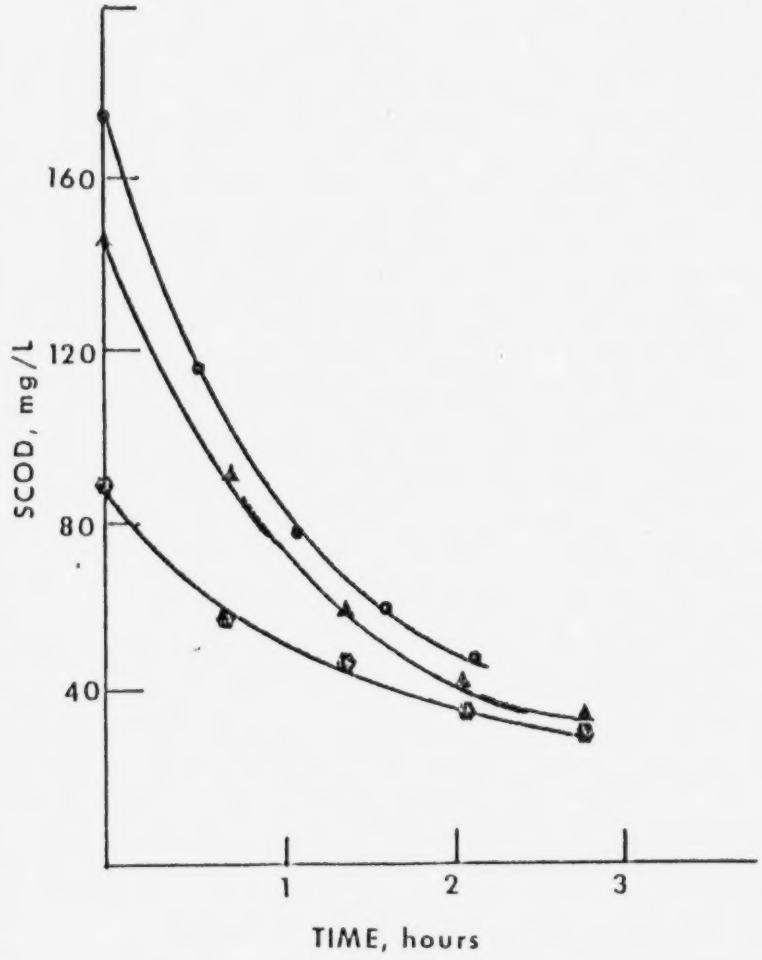

Figure 3. Mechanical drive — Disappearance of sCOD with time .

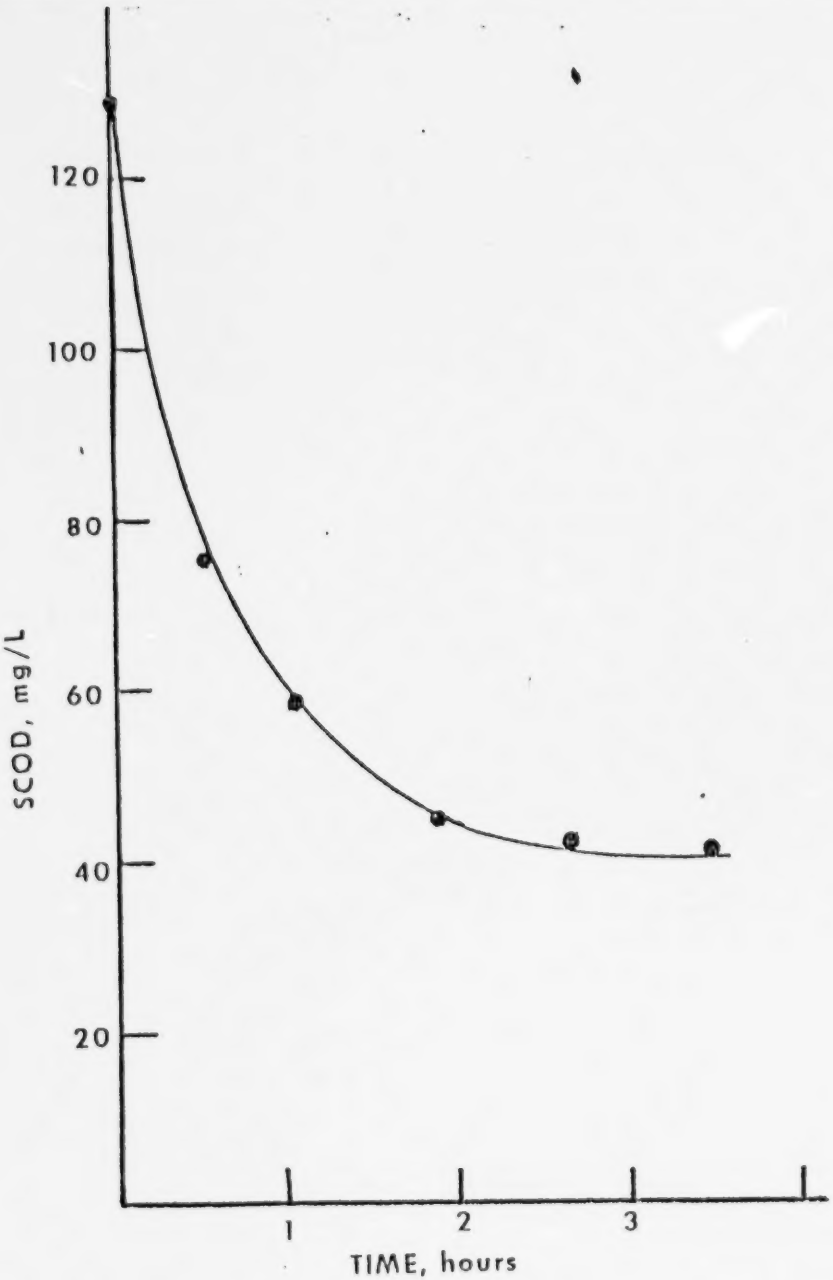

Figure 4. LeSourdsville—
Disappearance of sCOD with time.

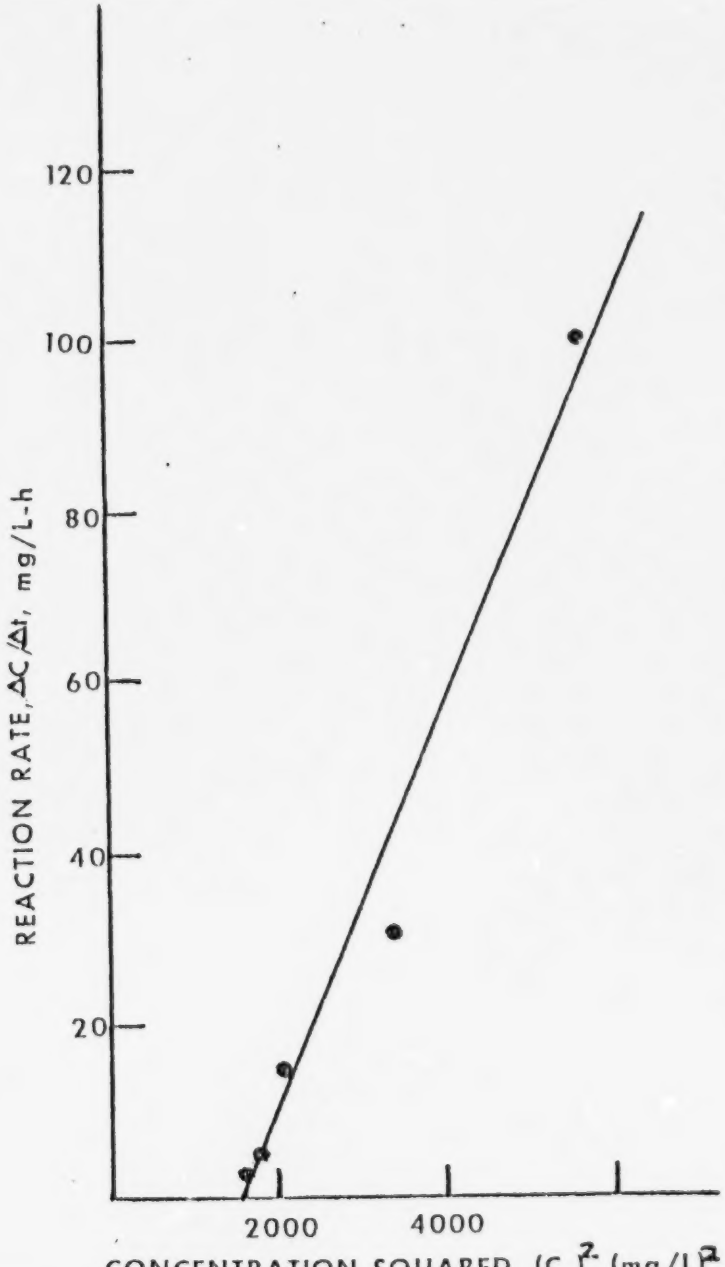

Figure 5. LeSourdsville
Reaction rate at various concentrations squared.

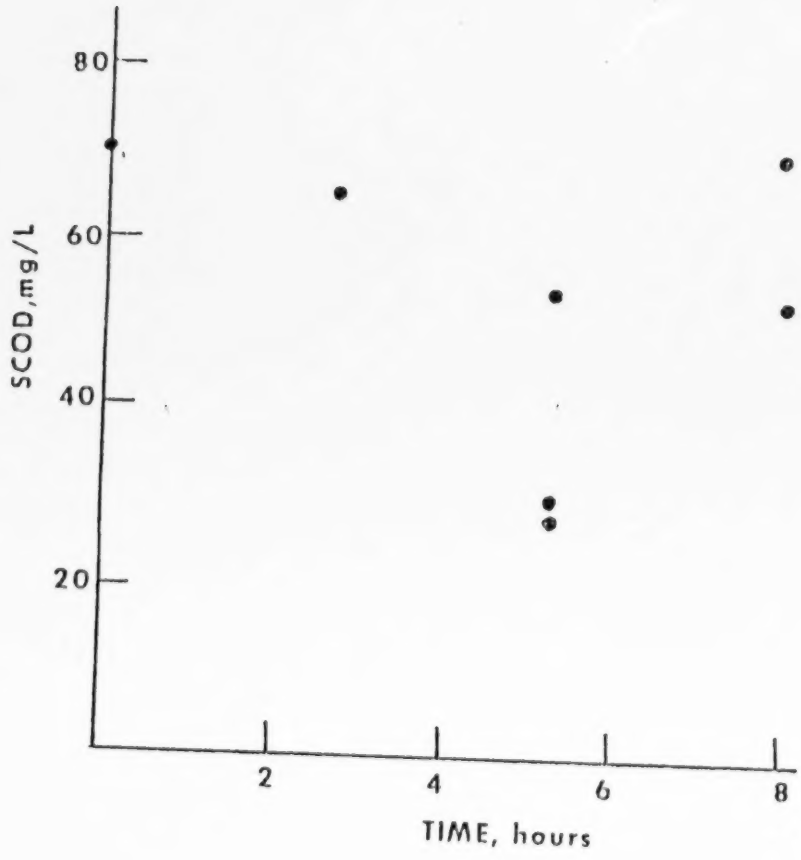

Figure 6. Scatter on disappearance of sCOD with time.

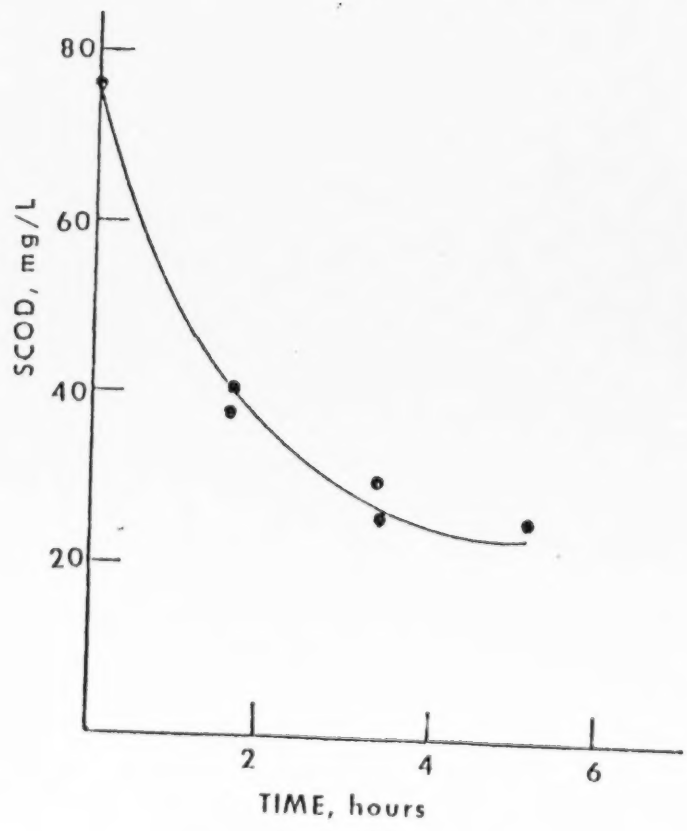

Figure 7. Indian Creek — Disappearance of sCOD with time.

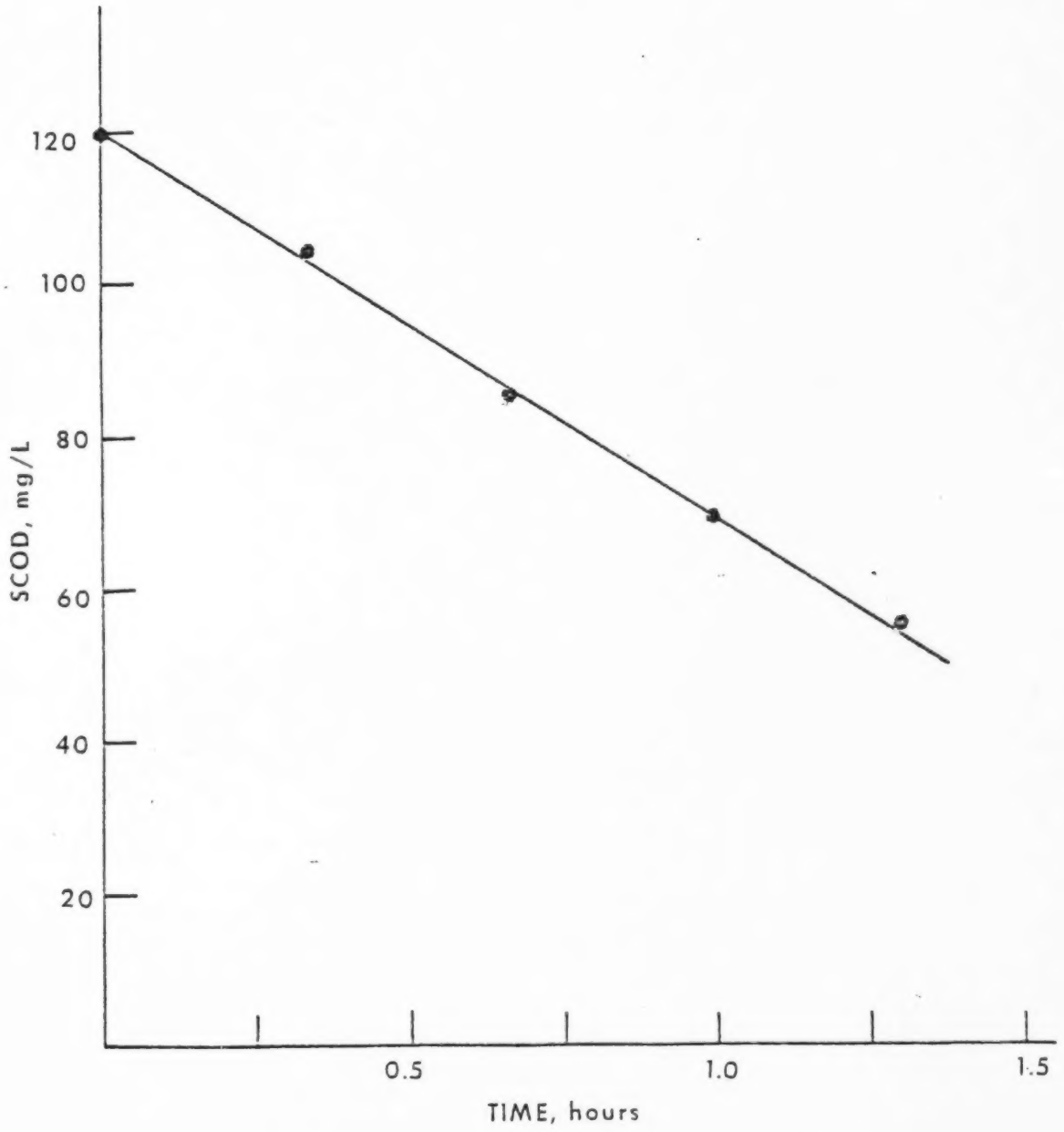

Figure 8, Hynek — Disappearance of sCOD with time.

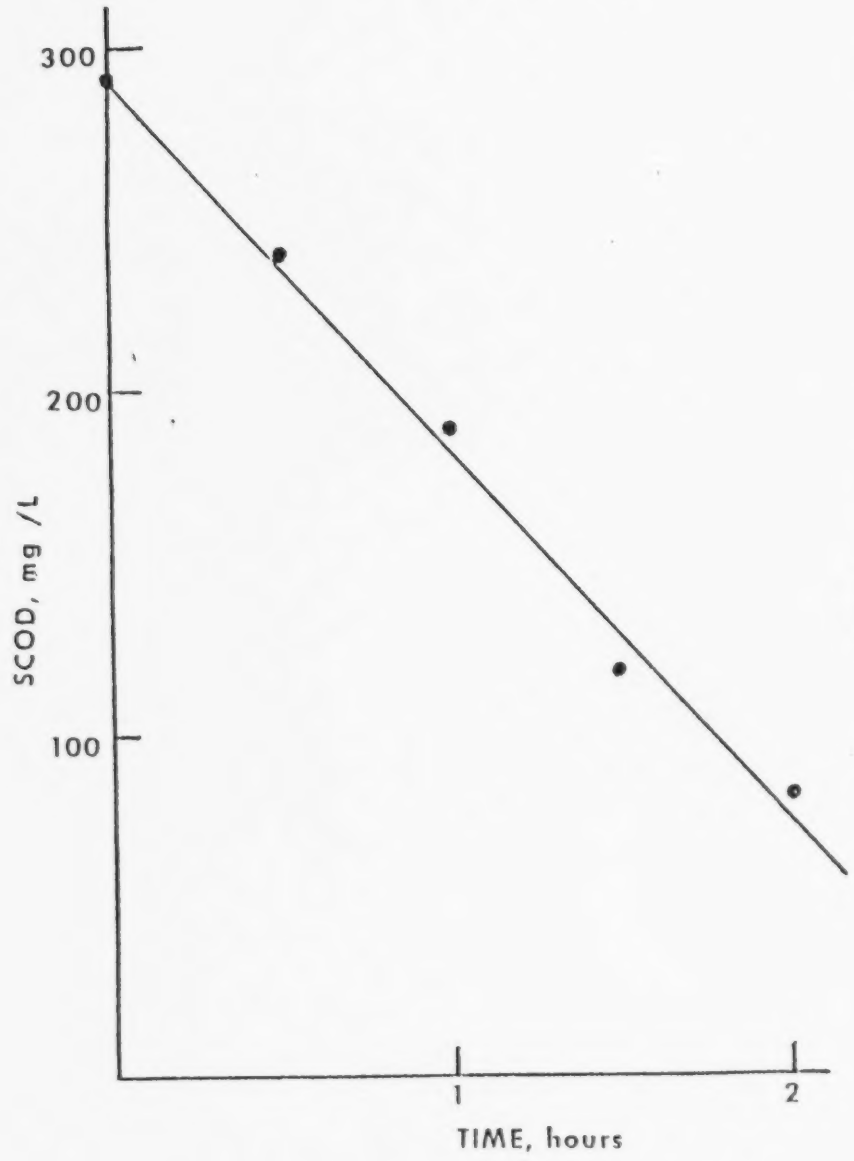

Figure 9.Brookville Disappearance of sCOD with time.

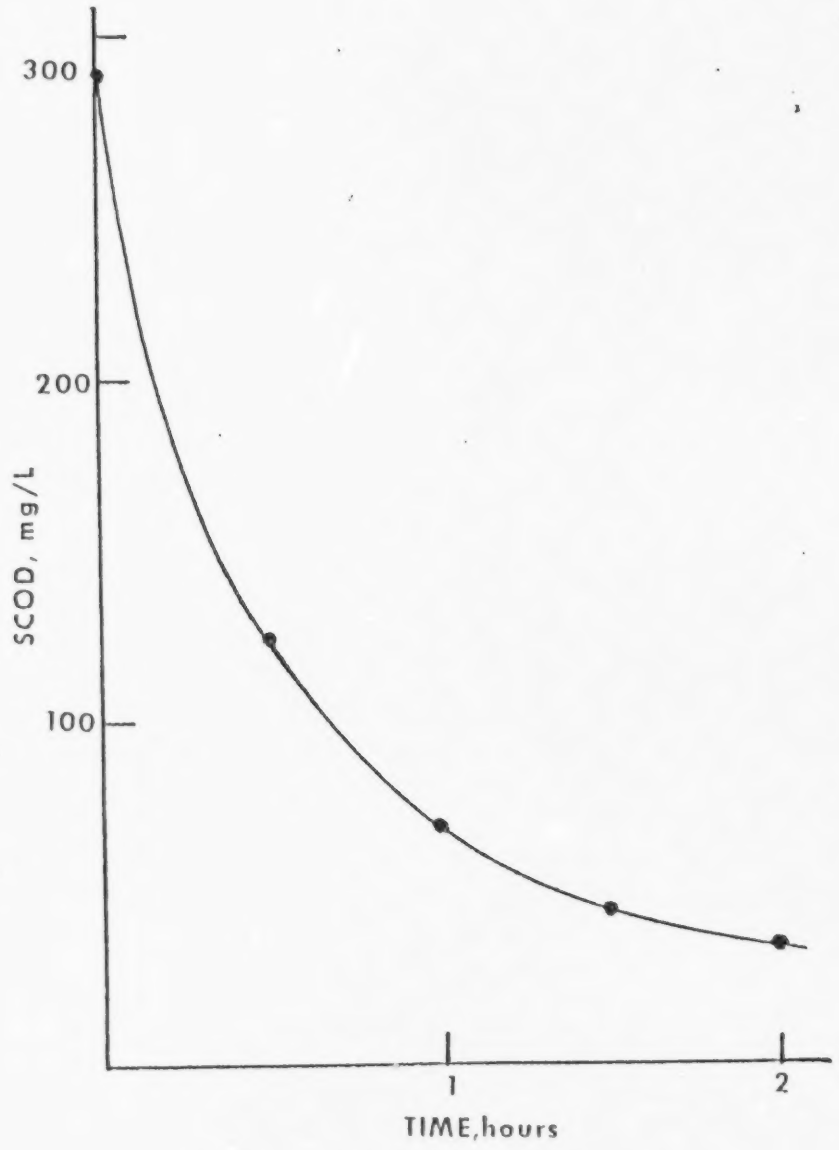

Figure 10. Disappearance of sCOD with time assuming second order kinetics.